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RE-EVALUATION OF THE NORSAR DETECTION AND LOCATION CAPABILITIES

by

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the incremental methods as expected give higher thresholds; for example, for the Japan-Kuriles-Kamchatka region the three methods give, for the 90% detectability, values at NORSAR magnitudes 3.8, 3.9 and 4.0, respectively. The b-values have also been estimated using a weighted least squares method and the Utsu method, and the median of the b-values from the five techniques are for all regions in the range 0.7 to 1.1, with some regional variations. An extensive comparison with PDE solutions from USGS shows that NORSAR generally reports somewhat smaller magnitudes. The event locations as published by NORSAR since the beginning of 1973 are generally better than before. For the best regions the median location difference between NORSAR and USGS estimates is about 100 km, and very few regions show any significant difference between the average distances and azimuths as reported by the two institutions.

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ABSTRACT

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1. INTRODUCTION

The construction of the large seismic arrays LASA and NORSAR during the time period 1965-1971 were major events in the development of observational seismology. The data from these arrays have been used in the investigation of a wide range of seismological problems, even though the main purpose was the more limited one of finding ways and means to detect, locate and identify small seismic events. During the first few years after the arrays were completed, a large number of reports and papers were published in which the capabilities of the arrays in this respect were investigated. However, these studies were mostly based on data collected during the more initial phases of operation, so that their results were often affected by 1) later improvements and changes, and 2) not having collected enough data. Also, different methods have been used in the evaluations, all these being the reasons why many relatively different results were produced, especially on detection capabilities.

The latest and most complete report on the capability of the NORSAR array to detect and locate seismic events was published by Bungum and Husebye (1974). In that study, the detection capability was investigated using data for the time period April 1972-March 1973, while for the location capability data covering the time interval February-November 1972 were used. Data for two more years are now available, during which time the operational situation has been fairly stable, and the purpose of this paper is to re-evaluate some of the results from Bungum and Husebye (1974). Also, several methods will be used this time to evaluate detection capability, and special attention will be given to the problem of estimating the recurrence parameter b.

2. THE NORSAR OPERATIONAL SITUATION

We refer to Bungum et al. (1971) and Bungum and Husebye (1974) for a comprehensive description of the NORSAR array, its physical configuration and instrumentation, and its data analysis procedures. However, since changes (albeit minor) have been implemented also after Bungum and Husebye (1974) published their paper, a short review of the operational situation is nevertheless warranted, and for the purpose of completeness we start with the initial NORSAR system.

The first seismic data at NORSAR was recorded in September 1969. Named Interim NORSAR, it included only a few sensors, for very limited time intervals, and was terminated in September 1970. At that time, the first recording using all 132 short period and 66 long period seismometers was initiated, and one started to experiment with the first full array beam deployment (called AB 306). The data recording intervals were still very limited. A new beam deployment (AB 310) was implemented in April 1971, at which time relatively regular data recording and analysis started. The whole year of 1971 was characterized by extensive software development, at the same time as the recording 'down time' was reduced to about 3%. In December of that year, another beam deployment (AB 401) was implemented, and in January 1972, one could introduce a new and much improved set of regional time delay and location corrections. The same month also saw the implementation of a more high frequent on-line band pass filter (1.2-3.2 Hz) which significantly improved the signal-to-noise ratios. Because of all these changes, the evaluation by Bungum and Husebye (1974) started with the data from February 1972.

A large number of modifications have been introduced also since then, although their overall effect has been less noticeable. In July 1972, the so-called incoherent beamforming was implemented (Ringdal et al., 1975), which improved the capability of the array to detect events within 30° epicentral distance. In November 1972, new regional time delay and location corrections were introduced, although the changes this time were minor and mainly effective only in areas of low seismic activity. The same can be said about the new beam deployment (AB 411) implemented in February 1973.

Other changes which took place during the evaluation period of this report were:

- regionalization of filter setting in Event Processor (EP) (February 1973);
- regionalization in EP of the slowness estimation procedure (beampacking vs. beamforming) (March 1973);
- more efficient screening in EP against local explosions (which represent a serious false alarm problem) (February 1974);
- implementation of weighted beamforming (Christoffersson and Husebye, 1974) in EP, to be used on specifically selected weak detections (December 1974); in the same package, a number of statistical tests to aid in the signal identification (Fyen et al., 1975) were implemented (December 1974);
- implementation of a floating processing threshold in EP (Steinert et al., 1975) for the purpose of keeping a constant false alarm rate, thus countering diurnal variations in the noise varianse (December 1974).

3. THE NORSAR DETECTIC APABILITY

The time interval used in the detectability calculations by Bungum and Husebye (1974) was from April 1972 to March 1973, during which time about 5500 events were reported by NORSAR. The data were grouped into 15 regions, a regionalization which has been adopted also for this paper (Table 1). The first data column in Table 1 shows the number of events analyzed by Bungum and Husebye (1974) in each of the regions; it is seen that for two of the regions the number is less than 100, which naturally makes a detectability estimate quite uncertain. The number of events for the next two years (Table 1) shows a considerable variation for some regions, the reason for that is most likely not variation in detectability but rather variation in seismicity, which emphasizes the importance of using sufficiently long time intervals in this type of analysis.

Cumulative Event Detection Capability of the Array

Using the same method as Bungum and Husebye (1974), we computed the 50% and 90% cumulative detectability estimates for each of the three consecutive years covered by this report, as well as the results for the three years combined, and the results are shown in Table 2. The method is briefly as follows: A straight line is fitted (see Fig. 1), using the method of least squares, through the part of the (cumulative or incremental) log frequency-magnitude distribution which is between two magnitude limits. These limits are defined by the analyst so as to cover a reasonably straight portion of the distribution. The 90% and the 50% detectability limits are then defined as the magnitudes at which the actual number of events falls 10% and 50%, respectively, below the level predicted by the extrapolation of the calculated frequency-magnitude distribution towards lower magnitudes.

Although there is a better performance for some of the regions in the last period (1974/75), the trend is towards slightly higher thresholds. This is probably not caused by a real deteriorating performance, but rather indicates that the false alarm problem has been better handled in the later years, thus giving fewer events reported at low magnitudes. The main impression is, however, that there is a remarkable stability in the performance over the three years, thus giving a consistent data base for threshold determination combining all three years. As an example of the fact that the changing seismicity level does not significantly affect the estimates of detection performance, we can look at the results for region 9 (Ryukuo-Philippines). In Table 1 it is seen that the number of events reported for this region is 961 in 1972/1973 and 466 in 1974/1975, while Table 2 shows that the detectability estimates for these two periods are essentially unchanged.

The obtained results show, as also demonstrated by Bungum and Husebye (1974), that the best results are achieved for regions 5-8 which cover the belt through the Mediterranean, Iran, Western Russia, Central Asia to Southeast Asia. All of these regions are located on the same (Eurasian) tectonic plate as NORSAR. Within 90 degrees distance range from NORSAR then follow the Aleutian-Alaska region, Japan-Kamchatka, Western-Northern America and the Mid-Atlantic Ridge, while the poorest performance is obtained for the Central America and the Ryukuo-Philippines regions. As pointed out by Bungum and Husebye (1974), the regions where NORSAR has the best detectability performance are the regions where the average signal frequency is high, while generally the regions where NORSAR has a poorer performance are the regions from where lower frequencies are observed.

Incremental Detection Capability

It is sometimes desirable to specify the incremental detection capability of a station, i.e., the probability of detecting an event of a given magnitude. It is clear that the incremental detection thresholds should always be higher than the cumulative ones. Lacoss (1971) computed the expected differences

Table 1

Number of events reported by NORSAR for the intervals April 1972-March 1973, April 1973-March 1974, April 1974-March 1975 and April 1972-March 1975.

REGION	AREA OF COVERAGE	1972/1973	1973/1974	1974/1975	1972/1975
1	Aleutians-Alaska	392	319	397	1108
2	Western North America	99	91	42	232
3	Central America	138	88	102	328
4	Mid-Atlantic Ridge	147	151	184	482
5	Mediterranean-Middle East	466	409	469	1344
6	Iran-Western Russia	386	241	263	890
7	Central Asia	524	396	770	1690
8	Southern-Eastern Asia	299	290	453	1042
9	Ryukuo-Philippines	961	546	466	1973
10	Japan-Kamchatka	841	1395	912	3148
11	New Guinea-Hebrides	146	238	141	525
12	Fiji-Kermadec	663	777	799	2239
13	South America	88	91	165	344
14	Distance Range 30^o-90^o	4335	4011	4278	12624
15	Distance Range 110^o-180^o	1057	1298	1188	3543

Table 2

Cumulative 50 and 90 per cent detection thresholds in terms of NORSAR m_b units for the intervals April 1972-March 1973, April 1973-March 1974, April 1974-March 1975 and April 1972-March 1975. A dash indicates that there were too few data or a too difficult distribution for detectability estimates.

REGION	1972/1973		1973/1974		1974/1975		1972/1975	
	MB-50	MB-90	MB-50	MB-90	MB-50	MB-90	MB-50	MB-90
1	-	3.6	3.4	3.8	3.4	3.8	3.4	3.7
2	-	-	3.5	4.0	-	-	-	3.8
3	3.7	4.1	3.9	4.4	3.8	4.3	3.8	4.3
4	-	3.5	3.5	3.9	3.4	3.8	3.4	3.8
5	3.0	3.6	3.0	3.7	3.3	3.8	3.1	3.6
6	3.4	3.8	3.3	3.8	3.1	3.5	3.3	3.7
7	3.2	3.6	3.1	3.5	3.1	3.5	3.1	3.5
8	-	3.4	3.2	3.6	3.3	3.7	3.2	3.6
9	4.0	4.5	3.9	4.5	3.9	4.4	3.9	4.5
10	3.4	3.9	3.3	3.7	3.4	3.9	3.4	3.8
11	4.0	4.4	4.3	4.6	4.2	4.6	4.1	4.5
12	3.4	3.9	3.3	3.9	3.4	3.9	3.4	3.9
13	4.4	4.7	4.2	4.9	4.4	4.9	4.3	4.8
14	3.4	3.8	3.4	3.9	3.5	3.9	3.4	3.9
15	4.0	4.5	4.2	4.6	4.3	4.7	4.2	4.6

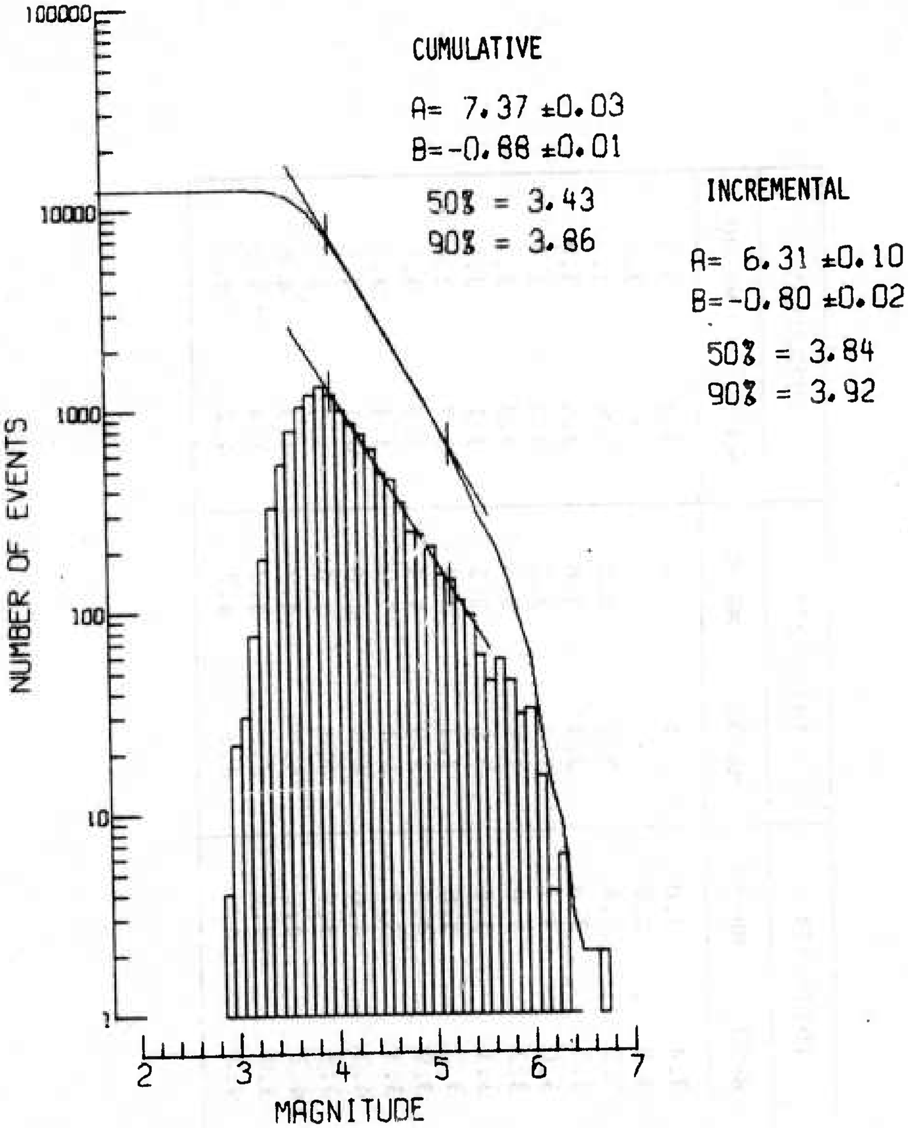

Fig. 1 Frequency-magnitude distribution for region 14 for April 1972 - March 1975. Cumulative and incremental detectability levels are indicated.

between the two cases based on a Gaussian detectability curve. He found values typically in the range 0.1-0.4 m_b units, and with a somewhat larger difference for 50 per cent thresholds than at the 90 per cent level.

Several techniques have been devised to estimate the incremental detectability of a seismic station. For example, the method described previously for the cumulative case can be applied to the incremental case as well, and the results are presented in Table 3. It should be noted, however, that the estimates by this method are quite unstable; mostly because of the difficulties inherent in estimating the incremental seismicity slope by least squares. A different approach has been used by Lacoss and Kelly (1969), who applied a maximum-likelihood technique to simultaneously estimate seismicity and detection thresholds. Briefly, their method assumes that the number of earthquakes N_c exceeding a given magnitude m is specified by

$$\log_{10} N_c = a - b \cdot m \tag{1}$$

and that the detection probability of a station, given the event magnitude m at the station itself, is of the form:

$$P(\text{Detect}/m) = \Phi\left(\frac{m-\mu}{\sigma}\right) \tag{2}$$

where Φ is the standard cumulative Gaussian distribution function. The four unknown parameters a, b, μ and σ may then be estimated by maximizing the likelihood function:

$$L(a,b,\mu,\sigma) = \exp(-N) \cdot \prod_{i=1}^{K} \cdot 10^{a-bm_i} \cdot \Phi\left(\frac{m_i-\mu}{\sigma}\right) \tag{3}$$

Here, $m_i,\ldots,m_K$ represent the measured magnitudes of all detected events, and N is the total expected number of detected events:

$$\log_{10} N = a - b\mu + b^2 \cdot \sigma^2/(2 \cdot \log_{10} e) \tag{4}$$

Table 4 presents the results from incremental threshold estimation using the technique of Lacoss-Kelly. It is instructive to compare these results to those obtained previously. We see that, for the regions with the largest number of events, the two incremental techniques agree fairly well, and generally give higher results than the cumulative method. For example, looking at region 10 (Japan-Kuriles-Kamchatka) for 1972-75, we obtain, for 50 and 90 per cent thresholds, respectively: 3.4 and 3.8 (cumulative), 3.7 and 3.9 (incremental, least squares) and 3.7 and 4.0 (Lacoss-Kelly).

It should be noted that the estimation results quoted in this section always refer to detection thresholds in terms of NORSAR magnitudes. As shown by Ringdal (1975), the curve (2) can in principle easily be converted to a 'true' detection curve (i.e., the probability of detection as a function of a hypothetical true magnitude), if one assumes that NORSAR m_b is normally distributed ($m+b_N$, σ_N^2) for any given event of true magnitude m. The true detection curve then becomes:

$$P(\text{detect/true } m) = \Phi\left(\frac{m-\mu+b_N}{\sqrt{\sigma^2+\sigma_N^2}}\right) \qquad (5)$$

Assuming $b_N=0$, $\sigma_N=0.25$, it follows that the incremental 50 per cent thresholds remain unchanged, while the 90 per cent values determined by the Lacoss-Kelly method must be incremented by about 0.15 m_b units.

Table 3

Same as Table 2 for the incremental detection thresholds

REGION	1972/1973		1973/1974		1974/1975		1972/1975	
	MB-50	MB-90	MB-50	MB-90	MB-50	MB-90	MB-50	MB-90
1	3.6	3.8	3.8	4.0	3.7	3.9	3.7	3.8
2	-	-	3.8	4.1	-	-	3.7	3.9
3	-	-	-	4.0	-	-	4.0	4.3
4	3.5	3.6	3.8	4.1	3.6	3.9	3.6	3.8
5	3.2	3.4	-	-	3.3	3.8	3.3	3.7
6	3.6	3.8	3.5	3.8	3.4	3.6	3.5	3.8
7	3.5	3.7	3.4	3.6	-	-	3.5	3.7
8	3.5	3.6	3.6	3.7	3.6	3.7	3.6	3.7
9	4.2	4.4	4.0	4.3	-	-	4.1	4.5
10	3.7	3.9	3.7	3.9	3.7	3.9	3.7	3.9
11	4.3	4.6	-	-	-	-	4.5	4.6
12	3.7	4.1	3.5	3.7	3.6	4.1	3.6	3.9
13	-	-	-	-	-	-	-	-
14	3.7	3.9	3.7	4.0	3.8	4.0	3.8	3.9
15	4.2	4.6	4.3	4.6	4.3	4.7	4.3	4.6

Table 4

Same as Table 2 for the incremental detection thresholds using the Lacoss and Kelly (1969) method of estimation.

REGION	1972/1973		1973/1974		1974/1975		1972/1975	
	MB-50	MB-90	MB-50	MB-90	MB-50	MB-90	MB-50	MB-90
1	3.7	3.9	3.8	4.1	3.8	4.0	3.8	4.0
2	3.7	3.8	4.1	4.4	3.9	4.1	3.8	4.0
3	4.1	4.4	4.2	4.5	4.1	4.4	4.1	4.4
4	3.6	3.8	4.2	-	3.9	4.2	3.9	4.2
5	3.3	3.5	3.3	3.7	3.4	3.8	3.3	3.7
6	3.6	3.9	3.7	4.1	3.5	3.8	3.6	4.0
7	3.6	3.8	3.5	3.7	3.4	3.7	3.5	3.8
8	3.6	3.7	3.6	3.9	3.7	4.0	3.6	3.9
9	4.1	4.5	4.1	4.5	4.0	4.3	4.1	4.5
10	3.8	4.0	3.7	4.0	3.8	4.1	3.7	4.0
11	4.4	4.7	4.7	5.0	4.4	4.7	4.5	4.9
12	3.7	4.0	3.5	3.8	3.7	4.0	3.6	3.9
13	4.7	5.2	4.5	5.0	4.2	4.7	4.4	4.9
14	3.7	4.0	3.8	4.2	3.8	4.2	3.8	4.1
15	4.3	4.8	4.6	5.3	4.5	5.1	4.5	5.1

4. CALCULATION OF THE RECURRENCE PARAMETER b

As a by-product of the detectability computations in the preceding section, we have obtained estimates of the seismicity recurrence parameters a and b in the formula (1). In fact, large arrays are particularly well suited to investigate regional seismicity, since they combine a good location capability with magnitude estimates that are consistent over the whole magnitude range. In contrast, seismic networks tend to overestimate magnitudes of small earthquakes (Herrin and Tucker, 1972), thereby distorting the frequency-magnitude relationship. Furthermore, the variance of array magnitude estimates relative to the "true magnitude" does not bias the estimation of b, and can be compensated for when estimating the a parameter (Ringdal, 1975).

In this section we summarize the estimation results of the parameter b of (1). In addition to the three methods discussed in the preceding section for detectability estimates, we have applied Utsu's (1965) maximum likelihood estimate

$$b = \frac{\log_{10} e}{\bar{m}-m_o} \qquad (6)$$

Here, perfect detectability is assumed down to a magnitude m_o, and $\bar{m}$ is the average of all observed magnitudes exceeding m_o.

We also attempt to modify the least squares procedure for incremental estimation by weighing each data point (m_i, log N_i) by the weight factor N_i (i.e., the number of observations at the magnitude m_i).

The results from the five methods of estimation are shown in Table 5. The entire data set 1972-75 has been used, with the same regionalization as before. We note that the results show occasional large variation between the different techniques, while some common trends are also noted. As an example, the two incremental least squares methods (2 and 3) generally produce the lowest b-values. This was to be expected, since the slope b' of the 'incremental' relationship

$$\log N_I = a' - b'm \tag{7}$$

is not necessarily equal to b in (1). It is clear that b=b' if (1) is valid without any restriction on m, while if one assumes a certain highest possible magnitude value, then the cumulative slope will tend to decrease more steeply than the incremental slope.

There is clearly a high amount of uncertainty involved in interpreting the data of Table 5. However, we note that the median value for all regions lies between 0.7 and 1.1. Examining more closely the regions within the teleseismic zone, we see that regions 1, 2 and 10 (covering the seismicity belt from Japan to Western North America) all have b-values at or below 0.80, while the Eurasian regions 5 and 6 exceed 1.0. Thus, there are differences of some significance in these data, in spite of the large amount of smoothing introduced by our large-scale regionalization. It would be of considerable interest to use NORSAR data to obtain b-values at a more detailed regional level. Also, it would be interesting to discuss more closely the relative merits of the various estimation techniques. Both of these topics are, however, outside the scope of the present paper.

Table 5

Observed b-values for different estimation procedures.

REGION	1. CUMULATIVE LEAST SQUARES	2. INCREMENTAL LEAST SQUARES	3. INCREMENTAL WEIGHTED LEAST SQUARES	4. LACOSS AND KELLY	5. UTSU	MEDIAN VALUE
1	0.80 ± 0.01	0.73 ± 0.05	0.74 ± 0.03	0.85	0.82	0.80
2	0.75 ± 0.01	0.68 ± 0.11	0.46 ± 0.08	0.80	0.74	0.74
3	0.94 ± 0.02	0.80 ± 0.10	0.53 ± 0.07	0.94	0.87	0.87
4	0.87 ± 0.04	0.56 ± 0.08	0.52 ± 0.04	1.06	0.82	0.82
5	1.07 ± 0.02	1.07 ± 0.08	0.86 ± 0.06	1.03	0.96	1.02
6	1.04 ± 0.03	0.94 ± 0.06	1.02 ± 0.07	1.10	1.02	1.02
7	0.85 ± 0.01	0.82 ± 0.06	0.77 ± 0.02	0.89	0.88	0.85
8	0.86 ± 0.01	0.82 ± 0.07	0.72 ± 0.04	0.95	0.89	0.86
9	1.13 ± 0.02	1.01 ± 0.05	0.78 ± 0.03	1.02	0.95	1.01
10	0.80 ± 0.01	0.73 ± 0.03	0.67 ± 0.03	0.83	0.79	0.79
11	1.05 ± 0.02	1.07 ± 0.08	0.79 ± 0.07	1.18	1.06	1.06
12	0.85 ± 0.01	0.72 ± 0.04	0.64 ± 0.02	0.81	0.81	0.81
13	0.95 ± 0.03		0.66 ± 0.05	0.82	0.83	0.83
14	0.88 ± 0.01	0.80 ± 0.02	0.79 ± 0.01	0.93	0.87	0.87
15	1.13 ± 0.02	0.95 ± 0.02	0.91 ± 0.06	1.13	1.03	1.03

5. COMPARISON BETWEEN NORSAR AND USGS BODY WAVE MAGNITUDES

Comparing magnitudes reported by an array like NORSAR with those reported by a network like USGS is a hazardous task for several reasons. If NORSAR did not have any amplitude saturation problems, the best procedure would be to use only very high m_b events, say above m_b=6. This is because for such events a large number of stations and not only the best ones would report to USGS, thus one would not expect a bias in the USGS magnitude. Secondly, for such events NORSAR would have essentially 100 per cent detectability, and no bias would be introduced by the fact that one would select only those events detected by NORSAR, and thereby only those with particularly high NORSAR amplitudes. NORSAR does, however, have severe clipping problems, and since it is difficult to define an interval where we expect the magnitudes to be unbiased, we have used all events jointly reported by USGS and NORSAR in the period January 1973-March 1975. In Table 6 is listed the average magnitude difference together with standard deviation and number of events used. As seen from the table there is for all regions a positive difference, i.e., NORSAR seems to be reporting smaller magnitudes. As pointed out by Husebye et al. (1974), such differences cannot directly be explained as being caused by beamforming loss because the skew amplitude distribution gives a positive bias to the array beam, which roughly compensates the loss caused by incoherent signals. In Table 6 is also listed the results of a linear least squares fit through the NORSAR/USGS magnitude distribution, where a maximum likelihood method has been used. As seen from Table 6 there are clear regional variations in the NORSAR/USGS magnitude relationship. It should, however, be stressed that we have no control over different types of 'bias' effects influencing the results in Table 6.

Table 6

Estimates of average and standard deviation of the difference between USGS and NORSAR body wave magnitudes together with the standard errors in the estimates. The two last columns give maximum likelihood estimate of λ and K in the relation $m_b(\text{USGS})=\lambda+K\cdot m_b(\text{NORSAR})$.

REGION	EVENTS	AVERAGE	ST. DEV.	λ	K
1	454	0.20 ± 0.02	0.31 ± 0.01	0.55	0.92
2	127	0.28 ± 0.03	0.28 ± 0.02	0.08	1.05
3	121	0.18 ± 0.03	0.29 ± 0.08	0.62	0.91
4	136	0.31 ± 0.02	0.23 ± 0.01	0.87	0.88
5	297	0.36 ± 0.02	0.28 ± 0.01	0.25	1.03
6	139	0.27 ± 0.02	0.24 ± 0.01	0.79	0.88
7	334	0.23 ± 0.02	0.31 ± 0.01	0.39	0.96
8	201	0.33 ± 0.02	0.24 ± 0.01	1.17	0.82
9	365	0.20 ± 0.02	0.30 ± 0.01	1.02	0.83
10	1052	0.08 ± 0.01	0.28 ± 0.01	0.38	0.94
11	180	0.20 ± 0.03	0.36 ± 0.02	-0.19	1.08
12	367	0.21 ± 0.02	0.37 ± 0.01	1.33	0.76
13	98	0.18 ± 0.03	0.34 ± 0.02	1.11	0.82
14	3627	0.18 ± 0.01	0.30 ± 0.01	0.51	0.93
15	897	0.29 ± 0.01	0.35 ± 0.01	0.68	0.92

6. THE NORSAR LOCATION CAPABILITY

The difference in epicenter solutions has been calculated for the events reported jointly by USGS and NORSAR in the period January 1973 until March 1975. Fig. 2 presents the results for region 14 (distance limits 30-90 degrees from NORSAR) in increments of 50 km location difference. Fig. 3 shows the same data for the interval February to November 1972. It is seen that the distribution in Fig. 2 has a much shorter tail, indicating that most of the large location errors have been removed. Since the distributions are skew, the 50 per cent (median) and the 90 per cent level of location differences are used as characterizing parameters. In Table 7 the values observed for the period February to November 1972 (Bungum and Husebye, 1974) are listed together with the values observed for the period January 1973 until March 1975. For regions 5, 6, and 7 there is some tendency towards higher values in the last period; this is because no detailed analysis is performed for some of the nearest events; the event is instead located at the beam location where it was detected. For all the other regions there is a clear tendency towards a reduction in location differences. This is partly due to the implementation of new region corrections in November 1972, and partly due to more experienced analysts.

In Table 8 the location difference has been split into distance and azimuth differences. Also here are the averages as well as the standard deviations usually substantially reduced in the last period relative to the first one. It is, for example, seen that in the last period only one region has an azimuth difference which in average is more than one degree, and only two regions have distance differences with an average of more than 100 km. It is noteworthy that some of this scatter necessarily is introduced by the errors in the USGS estimates themselves. Based on these bias considerations as well as on independent theoretical estimates (Shlien and Toksöz, 1973) it can be concluded that the location precisions reported here for NORSAR are now at the performance limit for an array that size.

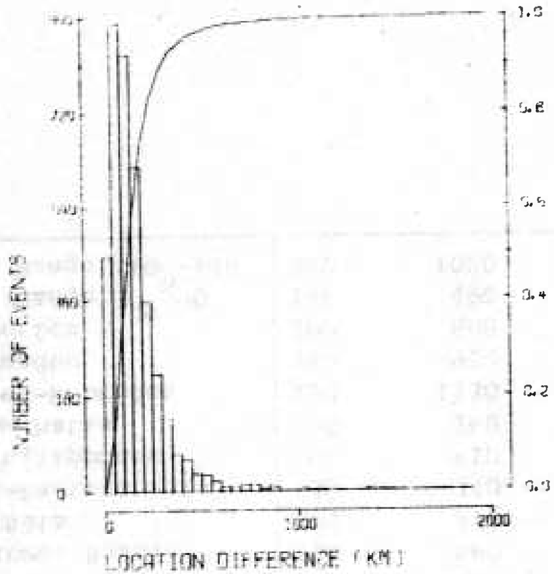

Fig.2. Cumulative and incremental distribution of epicenter location difference between USGS and NORSAR for region 14 (distance 30-90 degrees from NORSAR) for January 1973 until March 1975.

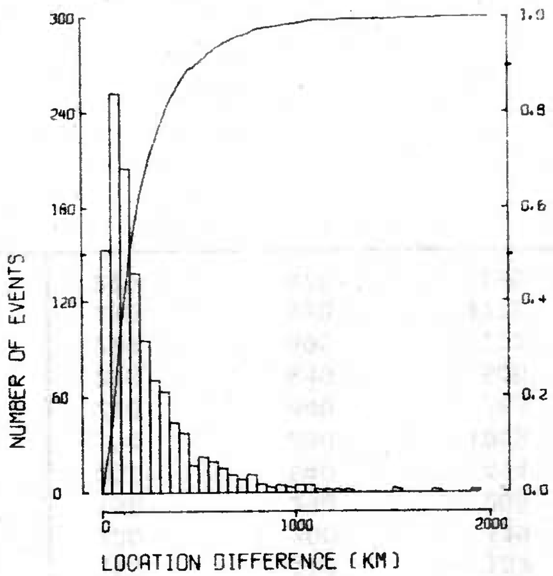

Fig. 3. Same as Fig. 2 for the time period February to November 1972 (from Bungum and Husebye, 1974).

Table 7

Estimates of median and 90 per cent location difference (in km) between USGS (PDE) and NORSAR epicenter solutions. N means number of events.

REGION	AREA OF COVERAGE	February - November 1972			January 1973 - March 1975		
		50%	90%	N	50%	90%	N
1	Aleutians-Alaska	135	330	157	110	220	461
2	Western North America	185	310	39	130	260	129
3	Central America	430	830	61	200	590	146
4	Mid-Atlantic Ridge	360	790	31	150	420	143
5	Mediterranean-Middle East	220	650	120	300	610	389
6	Iran-Western Russia	150	580	76	170	710	182
7	Central Asia	105	270	120	120	300	349
8	Southern-Eastern Asia	130	340	42	150	290	205
9	Ryukuo-Philippines	195	610	166	200	540	424
10	Japan-Kamchatka	95	260	255	100	230	1062
11	New Guinea-Hebrides	380	1330	87	210	840	263
12	Fiji-Kermadec	310	910	183	230	640	508
13	South America	390	680	33	210	495	112
14	Distance Range 30^{o}-90^{o}	145	490	1191	130	310	3775
15	Distance Range 110^{o}-180^{o}	320	1020	409	220	670	1195

Table 8

Average and standard deviation of distance and azimuth difference between USGS and NORSAR epicenter solution, together with standard errors in the estimates.

REGION	DISTANCE DIFFERENCE (km)				AZIMUTH DIFFERENCE (deg)			
	Feb-Nov 1972		Jan 1973-Mar 1975		Feb-Nov 1972		Jan 1973-Mar 1975	
	Average	St. Dev.	Average	St. Dev.	Average	St. Dev.	Average	St. Dev.
1	24±16	204±12	-14±6	124±4	0.32±0.06	0.79±0.04	0.07±0.04	0.84±0.03
2	94±15	95±11	37±11	122±8	-0.69±0.20	1.26±0.14	-0.30±0.14	1.06±0.07
3	-226±36	278±25	-138±21	259±15	-2.28±0.32	2.53±0.23	-1.28±0.13	1.60±0.09
4	188±164	911±117	14±35	415±25	1.38±0.22	1.21±0.15	0.28±0.09	1.09±0.06
5	14±29	316±20	61±17	335±12	-0.09±0.49	5.34±0.34	-0.16±0.21	4.14±0.15
6	22±35	303±25	-67±26	325±18	0.29±0.17	1.50±0.12	-0.63±0.14	1.81±0.10
7	-38±15	164±11	-35±10	190±7	0.04±0.07	0.72±0.05	-0.01±0.05	0.87±0.03
8	134±28	184±20	30±14	201±10	0.13±0.11	0.70±0.08	0.03±0.06	0.83±0.04
9	-61±27	343±19	86±15	299±10	-0.71±0.10	1.30±0.07	-0.14±0.07	1.38±0.05
10	-36±8	125±6	18±4	127±3	-0.28±0.06	0.94±0.04	-0.32±0.03	0.82±0.02
11	-152±70	654±50	-24±30	490±21	0.46±0.33	3.09±0.23	0.29±0.14	2.32±0.10
12	-216±31	422±22	-101±15	347±11	-0.75±0.30	4.02±0.21	-0.93±0.13	2.96±0.09
13	11±80	460±57	-1±24	256±17	1.47±0.35	2.01±0.25	0.31±0.17	1.81±0.12
14	-30±8	292±6	-26±3	200±2	-0.16±0.04	1.51±0.03	-0.10±0.02	1.21±0.01
15	-119±25	504±18	-33±11	392±8	0.11±0.18	3.70±0.13	-0.37±0.08	2.62±0.05

7. CONCLUSIONS

Based on analysis of NORSAR seismic bulletin data for the time period April 1972 - March 1975 we conclude that:

1) The detectability of the NORSAR array has not changed significantly with time during the three years analyzed.

2) For teleseismic (third zone) events, the detectability is highest for the regions between the Middle East and Southeast Asia, including Central Asia, and poorest for America and the North Atlantic Ridge.

3) The 90% incremental detectability thresholds for the best regions are in the range 3.7-3.9 measured on the NORSAR magnitude scale, while for the whole distance range 30°-90° the value is around 4.0.

4) The recurrence parameter b (the slope of the frequency-magnitude distribution) is found to be for all the regions in the range 0.7 to 1.1.

5) The relation between NORSAR and USGS reported magnitudes is dependent both on seismic region and magnitude, and include several bias effects. Generally, however, NORSAR reports smaller magnitudes.

6) The average location difference between NORSAR and USGS reported magnitudes is best for the regions Japan-Kamchatka, Aleutians-Alaska and Central Asia, where the median location difference is 100, 110 and 120 km, respectively. For the whole distance range 30°-90° from NORSAR, the corresponding number is 130 km.

7) The possible bias effects in the NORSAR location estimates are negligible, and no further significant improvement of the location precisions are now considered possible.

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